Characterizing Aerosol Processes and Properties for Reducing Uncertainties in Aerosol Radiative Forcing

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1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

One of the challenges for Earth System Science in the next decade is to improve the understanding of aerosol processes and properties in order to decrease uncertainties in estimates of global and regional aerosol radiative effects at the top of atmosphere, at the surface, and throughout the column.

Aerosols affect Earth's climate directly, by scattering and absorbing solar radiation, and indirectly by altering the lifetime and development of clouds, which in turn affect the scattering and absorption of radiation. Uncertainties associated with aerosol radiative forcing (ARF) estimates are among the leading causes of discrepancies in climate simulations and complicate Earth System studies that increasingly depend on understanding how atmospheric composition and its anthropogenic disturbances interact with other components of the Earth system. Therefore, detailed and accurate global aerosol measurements are required to better understand shortwave radiative transfer and to ultimately reduce climate change prediction uncertainties.

The latest IPCC model-based ARF estimate of radiative forcing due to aerosol–radiation interactions is –0.35 (–0.85 to +0.15) W/m^2. However, there remains considerable observational as well as recent modeling evidence that the actual uncertainty is a factor of two to four larger. Simply doubling the estimated uncertainty range would have a large impact on estimates of climate sensitivity and future predictions of surface temperature associated with climate change.

Reducing the uncertainty in direct aerosol radiative forcing (DARF) is a necessary step in reconciling estimates of radiative forcing and the equilibrium climate sensitivity of the Earth so that future predictions of surface temperature associated with climate change can be made with confidence. In particular, providing better observational constraints on anthropogenic aerosols and their microphysical properties, as represented in models, would significantly reduce uncertainty in DARF estimates. Quantitative improvement in DARF estimates will in turn increase confidence in estimating the sensitivity of the climate system to forcing by greenhouse gases. Furthermore, the top-of-atmosphere DARF estimate alone is insufficient to determine aerosol forcing at the surface and within the atmosphere; vertically resolved measurements are necessary to fully characterize DARF. The former affects processes such as photosynthesis and evapotranspiration, and the latter is critical to understanding how atmospheric heating by absorbing aerosols affects atmospheric stability structure, cloud development, atmospheric circulation and precipitation patterns.

The NASA Science Mission Directorate Workshop conducted in May 2014 (https://espo.nasa.gov/home/content/NASA_SMD_Workshop; hereafter the *SMD whitepaper*) identified aerosol impacts on Earth's radiation budget as a critical science area, and endorsed the fundamental science and observational requirements put forth in the NASA Aerosol-Cloud-Ecosystems (ACE) mission recommended by the 2007 Decadal Survey. In particular, the SMD whitepaper targets reduction in ARF uncertainties as a key community objective. Current A-Train measurements are insufficient to constrain the aerosol properties needed to reduce these uncertainties. Layer-resolved aerosol absorption, targeted by the ACE mission to derive accurate heating rates and quantify semi-direct effects of aerosols, is notably absent from quantitative A-Train capabilities and so is among the highest priority aerosol measurements identified in the SMD whitepaper.

The ACE strategy is to produce a comprehensive data set of three-dimensional aerosol optical (e.g. scattering, absorption) and microphysical (e.g. size, composition via refractive index) properties as a function of time and location to constrain global model ARF estimates. ACE would provide firm global and regional DARF estimates and uncertainties by confronting issues not adequately addressed by previous observations along with the first ever measurement-based estimate of the global direct aerosol radiative forcing at the bottom of the atmosphere to within ± 1 W/m^2. This is equivalent to estimating the global surface evaporation rate of ± 1 mm/month (~ 1% of global rates).

Fully understanding the role of aerosol in the climate system fundamentally requires understanding what determines current and future spatial and temporal aerosol distributions. In particular, this requires characterizing key sources, sinks and transport pathways of primary atmospheric aerosol properties and types, and determining the impact of aerosol events on the local, regional and global aerosol burden and air quality.

Although aerosols are locally or regionally generated, long-range transport of dust, pollution, and biomass burning aerosols contributes significantly to the aerosol loading in many locations. Severe aerosol pollution events and even background exposure are responsible for a range of chronic and acute respiratory ailments, causing an estimated two million premature deaths per year. About half of this mortality occurs in developing countries; however, even the average European loses 8.6 months of life expectancy due to exposure to fine particulate matter.

ACE measurements will better constrain global aerosol transport models. Determining aerosol source, sink, and transport properties requires synthesizing observations and global transport models, but evaluating how these models portray aerosol characteristics is also vital for reducing climate change simulation uncertainties and assessing and predicting air quality. The international Aerosol Comparisons between Observations and Models (AeroCom, http://aerocom.met.no/) project has involved most global aerosol modeling groups internationally over the past decade, providing a common framework for evaluation of global aerosol models and enhancing connections to aerosol data providers. AeroCom model intercomparisons of global mean aerosol optical thickness (AOT) typically match the values observed by satellites to within the satellite product uncertainties. However, AeroCom intercomparisons also revealed the wide diversity in how models estimate AOT, showing far less consensus on how models represent aerosol composition, particle size, and vertical profiles even when similar emission functions are used. In addition, the manner in which models use AOT to compute radiative forcing, which depends not only on aerosol distributions but also on the particle microphysical properties, is completely unconstrained on the global scale. Regional and seasonal distributions also show large diversity among models and between models and observations. These uncertainties lead to large differences in how models represent radiative heating rates and aerosol-cloud interactions, identify anthropogenic components, and assess the direct aerosol effect associated with long-term changes in aerosol distributions.

This model performance diversity exists largely because suitable measurements to constrain specific processes in the model simulations are lacking. Advanced global transport models now simulate aerosol mass, number, and size distributions for multiple aerosol compositions, modes, shapes and mixtures, so aerosol characterization now requires additional measurements beyond AOT or simple qualitative aerosol type descriptions. Specifically, layer-resolved aerosol composition to distinguish anthropogenic and natural aerosol components was identified as the second of two highest-priority aerosol measurements identified in the SMD report. Consequently, the ACE concept seeks to constrain model assumptions with satellite-derived estimates of source strength and location, vertical distribution, and distributions of AOT, mass, number, and composition, integrated with detailed measurements acquired from suborbital measurements.

2. Why are these challenge/questions timely to address now especially with respect to readiness?

Today the sensors aboard the A-Train and Terra satellites provide quantitative distributions of aerosol optical thickness in the horizontal, and retrievals of aerosol extinction profiles, as well as limited semi-quantitative information on aerosol absorption, size, and shape. However, the accuracy of these retrievals and even the ability to identify general aerosol air mass type in some circumstances, are insufficient for many climate- and health-related applications. For example, current satellite sensors measurements of AOT are inadequate to narrow DARF uncertainty estimates for climate change simulations.

Estimates of daytime aerosol vertical distribution are noisy, requiring spatial averaging that severely degrades horizontal resolution. Currently, there are no direct satellite measurements of aerosol extinction profiles. Other aerosol properties (absorption, size and shape) are difficult to measure in all situations from space with current instruments and are prone to large uncertainties. Determination of aerosol composition and anthropogenic fraction from space is based largely on assumptions rather than quantitative measurements. Aerosol retrievals from current passive space-based instruments degrade in the vicinity of clouds. Finally, EOS satellites have long since exceeded their design lifetimes and the A-train is expected to disband in the next few years.

The NASA ACE Pre-formulation Study played a major role in developing and demonstrating new satellite and sub-orbital instruments and advanced retrieval algorithms for answering these questions. Suborbital instruments inspired by ACE have already begun acquiring these new datasets during recent airborne field missions sponsored by NASA and other U.S. agencies. These new instruments have demonstrated the capability to provide unprecedented measurements of both column and layer resolved aerosol properties required to meet the objectives described above. The lidar, radar, polarimeter and ocean sensor technology that comprises ACE's core measurement suite is expected to reach a technological readiness level that will permit ACE to go in full formulation phase by the time the 2017 Decadal Survey Report is published.

3. Why are space-based observations fundamental to addressing these challenges/questions?

Aerosols originate from a wide variety of both natural (desert dust; sea spray; biogenic sulfate, nitrate, and carbonaceous particles; wildfire smoke; and volcanic ash) and anthropogenic (domestic, industrial, and transportation-related combustion, land use change, such as draining water resources, over-grazing, construction, and agricultural burning) sources. Consequently, they exhibit an exceedingly wide range of light absorption and scattering properties, chemical compositions, shapes, atmospheric lifetimes, and spatial distributions. Within the troposphere, aerosol lifetimes are typically about a week, so that aerosol amount and composition vary dramatically with space, time, and altitude. Only satellite measurements can provide the frequent, global coverage necessary for characterizing and quantifying this variability. Satellite measurements already provide critical data for studying aerosol impacts on the global energy budget, long range transport, aerosol model validation and assimilation, and air quality. Similarly, satellite measurements of the global distribution of aerosol absorption, composition, and size obtained from the ACE instruments would provide the constraints for reducing model diversity and climate simulation uncertainty.